The behaviour of exciton–polaritons

To the Editor — In a recent correspondence, Butov and Kavokin discussed exciton–polaritons and their transition into a coherent state[1]. In particular, they wished to point out that describing polaritons and their coherent state in terms of a Bose–Einstein condensate (BEC) and superfluidity may not be appropriate. However, I cannot agree with most of their comments.

Work on polariton quantum fluids and condensates flourished following our observation of a polariton BEC[2]. Our claim was based mainly on the spontaneous appearance of long-range order from a thermalized polariton cloud, in addition to all other properties expected for a BEC, such as a Bose distribution of polaritons. Condensation effects have subsequently been reported in many different configurations, and even up to room temperature[3].

Butov and Kavokin state that the "long-range coherence of polaritons is governed by their photonic component". The ordering of polariton condensates has been observed by different groups across a range of samples. This ordering is not governed by the photonic component of the polariton. The condensate self-orders in the regime of positive detuning; that is, when the exciton fraction in the polariton is larger than 0.5, which provides a higher polariton collision rate and therefore faster thermalization. Ordering also takes place at negative detuning, where the system does not have time to reach full thermal equilibrium. All experimental observations are accurately reproduced by dynamical Gross–Pitaevskii equations for the lower polariton branch, where the important ingredient is the interaction between polaritons; that is, the excitonic fraction. However, contrary to what Butov and Kavokin imply, we are still awaiting for a clear demonstration of BEC for the case of excitons, whether standard or indirect.

Discussion within the polariton community about the best way to qualify this observed phenomenon is linked with the fact that polaritons are part-light, part-matter quasiparticles, and that polariton condensates form two populations in a system: polaritons around the lower energy minimum of the dispersion, and polaritons with larger momenta at the 'reservoir'. These two populations are weakly coupled, which allows us to define a quasi-thermal equilibrium for each. Although they have a very short lifetime, polaritons in the lower branch are able to come to thermal equilibrium, and the condensate builds up from this thermal cloud, as expected for a BEC. The condensation of quasiparticles in solids, including exciton, polaritons, Cooper pairs and magnons, are usually described by disregarding various factors, starting with the crystal lattice.

The continuously adjustable proportion of exciton to photon in a polariton allows us to explore a wide range of its properties, ranging from very excitonic, where a condensed phase does not occur, to polaritons with a mass that allows for condensation, and thermalization below the threshold. We still observe the build-up of a coherent phase in lighter, more photonic polaritons. Such a condensed phase, usually called a 'polariton laser', differs strongly from conventional vertical-cavity surface-emitting lasers. This makes it possible with polaritons to change from a regime of condensation at quasi-equilibrium to a regime of condensation out of equilibrium.

Butov and Kavokin also contest the observation of polariton superfluidity. The original paper by Amo *et al.*[4] has been supported by a numerous collection of other studies. For low enough fluid speeds, there is no turbulence. For higher speeds, turbulence occurs in the form of dark solitons[5], quantized vortex pairs[6] and vortex streets[7]. Not only does the fluid exhibit long-range coherence far beyond the initial laser drive, but also dark solitons show the expected π phase shift and vortices exhibit the expected 2π phase shifts — all of which would be highly improbable in a conventional fluid.

Polaritons emit light by composition because their light component has a very short lifetime. This allows us to study their phase and coherence in a direct way that is not accessible to other bosonic quasiparticles. Nevertheless, polaritons do not behave as pure photons and undergo efficient interactions with their environment via their excitonic component. This allows manipulation via optical means[8] or observation of Josephson oscillations. Polaritons also carry a spin, which brings additional degrees of freedom. As outstanding examples, I could quote the observation of half vortices[9] or half solitons (G. Malpuech and A. Amo, private communication).

The limited space available in this letter has allowed me to give only a few experimental examples. The theoretical side of the field is progressing perhaps even more rapidly than the experimental side. To end on a positive note, I can easily agree with the last sentiment expressed by Butov and Kavokin: "The physics of polariton condensates, although different from that of atom BECs, is nevertheless rich and interesting." ☐

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